

Experimental Study to Determine Fast-Start Capability of On-Board Fuel Processors

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Abstract

Successful commercial deployment of on-board fuel processors for light-duty fuel cell vehicles will require rapid-start capability to deliver hydrogen to the fuel cell in 60 or fewer seconds. While it is known that the large thermal mass of the fuel processor is the principal cause that delays reaching the operating temperatures, theoretical considerations indicate that enabling the delivery of requisite energy reduces the issue to one of designing the fuel processor that can accommodate a rapid-start procedure.

This paper reports on the design of a laboratory-scale fuel processor suitable for on-board application, its design point, and the strategy being considered for meeting rapid-start targets. The strategy calls for heating only some critical elements initially, and simulations show that hydrogen of sufficient quantity and quality can be generated after 60 seconds for the fuel cell to produce power.

Introduction

Driven by the requirements for on-board fuel processing for fuel cells, the technology has seen some significant advances in the last decade. These include development of materials such as catalysts (reforming, shift, preferential oxidation, etc.), reagents (for sulfur, ammonia, etc.), chemical processes (pressure variations, thermal integration, gas separation and purification, etc.) and control. Fuel processors have been deployed, with successive generations demonstrating characteristics headed towards meeting target [1] size, weight, and performance criteria parameters.

The start-up times reported for these fuel processors have progressively diminished. General Motors announced a six-minute start-up of its gasoline fuel processor in 2002 [2]. It is estimated that motive power for start-and-drive consumers can be managed from storage devices (battery, pressurized hydrogen, etc.), provided the on-board fuel processor is able to deliver fuel-cell grade hydrogen in 30 seconds (or less). Thus on-board fuel processors need to meet the start-up time target along with all of the other targets that have to be met for successful commercialization.

Argonne National Laboratory is leading a collaborative effort with Los Alamos, Oak Ridge, and Pacific Northwest National Laboratories to study the feasibility of fast-starting a fuel processor. The study is being conducted through a combination of modeling and experimental activities that will lead to a laboratory-scale (10-kWe) fuel processor that can be started in 60 seconds (the U.S. Department of Energy's start-up time targets [1] are 60 seconds in 2005 and 30 seconds in 2010.) This paper presents the results of modeling the fuel processor and the design and operating parameters that have been chosen for the experimental apparatus.

Fuel Processor Layout and Design Point

The fuel processor design is based on an autothermal reformer (ATR), followed by a water-gas shift reactor, and a preferential oxidation unit. Figure 1 is a simplified schematic of the fuel processor. The water-gas shift reactor consists of four stages and the preferential oxidation unit consists of three stages. Heat exchangers are located after the ATR; after shift zones 1 and 2; and before preferential oxidation zones 1, 2, and 3. The heat removed from the reformate stream at the heat exchangers is used to boil and superheat the process water fed to the ATR. The cooling before shift zone 4 is achieved by direct injection of liquid water because this avoids using a heat exchanger for a heat removal load of only 0.3 kW. This is a small fraction of the heat load on the

heat exchangers, which combine for a total of 6.4 kW. Further, the addition of water favors the CO conversion in the low-temperature shift zone (WG4).

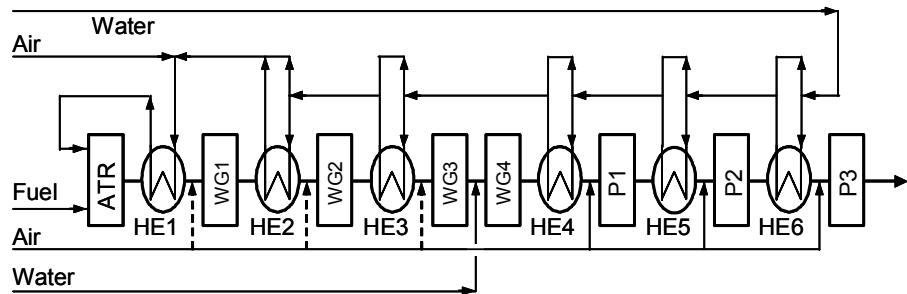


Figure 1. Simplified schematic of ATR-based gasoline fuel processor

Table 1 lists the gas hourly space velocities (GHSV) of the eight catalyst zones in the fuel processor. It also shows the steady-state temperatures and the concentrations of hydrogen, carbon monoxide, and water at the various locations in the fuel processor at the design capacity of 10 kWe. The shift reactor has a combined space velocity of 6,000 hr⁻¹ with the lowest temperature zone (WG4) representing 47% of the weight of the water-gas shift catalyst; yet it accounts for only 7% of the mols of CO converted in the water-gas shift reactor, i.e., WG4 reduces the CO concentration from 1.6% to 1.0%.

Table 1. Design and operating conditions of gasoline fuel processor

	ATR	WG1	WG2	WG3	WG4	P1	P2	P3
GHSV, per hr	74K	66K	41K	22K	13K	37K	37K	37K
Inlet Temperature, °C		375	350	300	280	140	140	100
Exit Temperature, °C	775	440	367	310	287	220	188	113
H ₂ at Exit, %-wet	31.8	37.5	39.1	39.9	39.7	38.7	37.7	37.5
CO at Exit, %-wet	9.7	4.0	2.5	1.6	1.0	0.3	0.1	0.001
H ₂ O at Exit, %-wet	23.9	18.1	16.6	15.8	16.9	16.9	17.2	17.2

There are six heat exchangers in the fuel processor. Cooling the reformatate at the ATR exit from 775°C to 375°C requires a heat removal (load) of 3.6 kW and is accomplished with a microchannel heat exchanger [3] designed and fabricated by Pacific Northwest National Laboratory. The five heat exchangers in the water-gas shift reactor and the preferential oxidation reactor have heat loads ranging from 0.6 to 1.3 kW. These are graphitic carbon foam heat exchangers [4] designed and fabricated by Oak Ridge National Laboratory.

Table 2. Heat exchanger loads in the fuel processor

	HE1	HE2	HE3	HE4	HE5	HE6
Heat Load, kW	3.6	0.8	0.6	1.3	0.7	0.8
Type:	Microchannel	Graphitic Carbon Foam				
Designed by:	Pacific Northwest National Lab.	Oak Ridge National Lab.				

The various components have been arranged in an array of concentric cylinders with the high-temperature components (ATR and HE1) located in the central cylinder, as shown in Figure 2. The first annular zone houses the first three zones of the shift reactor and two heat exchangers. The outer annular zone contains the last shift reactor zone, the three preferential oxidation reactors, and three heat exchangers as shown.

The fuel processor has been designed to be capable of meeting a start-up target time of 60 seconds. Start-up is defined as the ability to deliver 90% of the rated hydrogen production capacity (145 SLPM of hydrogen from this 10-kWe laboratory unit), where the reformatre contains greater than 30% hydrogen and less than 10 parts per million (ppm) of carbon monoxide. Some of the salient features of this design are as follows:

1. The fuel processor is based on the ATR because of its intrinsic ability to reach operating temperatures very quickly and thus deliver a mixture of hydrogen and carbon oxides.
2. The reformatre that is available from the ATR within a few seconds after ATR ignition will be oxidized with controlled injections of air in shift zones 1, 2, and 3 (shown as dotted lines in Fig. 1.)
3. Only some critical elements of the fuel processor will be heated initially to enable the fuel processor to meet the required hydrogen capacity within the designated start-up time.

Thus, the start-up process does not require heating of the large thermal mass in the low-temperature shift zone (WG4), and the preferential oxidation reactor has been sized to reduce up to 4% carbon monoxide from the shift reactor, down to 10 ppm. The catalyst chosen for the preferential oxidation reactor is known to be active at room temperature [5]. Similarly, the heat exchangers, needed for thermal integration to meet efficiency targets, are gradually heated up by the hot reformatre as the fuel processor continues to operate and approach steady-state conditions.

Figure 3 shows the simulated variations in the oxygen-to-carbon (O/C, refers to the oxygen from air into the ATR) and steam-to-carbon (S/C) ratios during the first 60 seconds. Even though referred to as the steam-to-carbon, the ATR receives and operates with atomized liquid water during most of the start-up period. The ATR is started with a relatively high O/C ratio of 1.5. The ATR temperature rise is restricted with increasing water (S/C) injection until it reaches 2.0, at which point the temperature rise is controlled by reducing the air feed rate and therefore the O/C ratio. Figure 3 also shows the hydrogen produced by the fuel processor, as a percentage of its capacity, which indicates that, under the simulated conditions, this fuel processor can meet its design goal of 90% of its hydrogen capacity within 60 seconds. Figure 4 shows the effect on the reformatre temperature as it exits the ATR, the heat exchanger HE1, and the shift zone WG3, all of which are at or close to their respective design temperatures after 60 seconds.

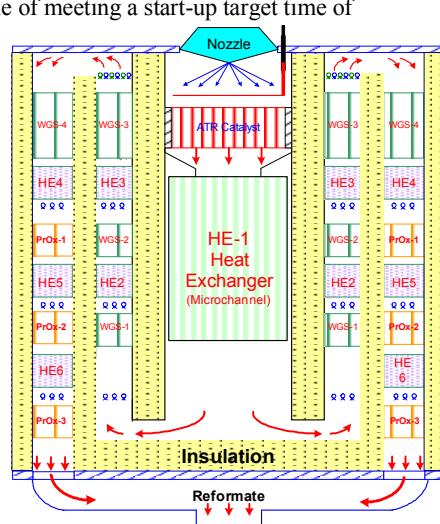


Figure 3. Schematic showing the layout of components in the fuel processor

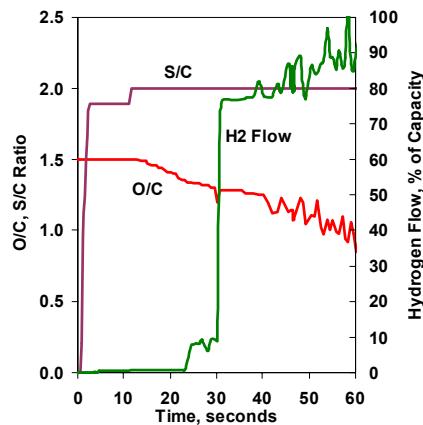


Figure 3. O/C ratio, S/C ratio, and hydrogen produced during the first 60 seconds of start-up

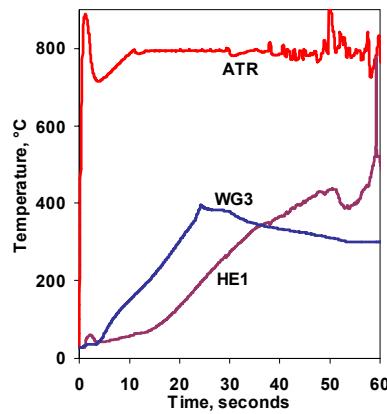


Figure 4. Temperatures of reformatte leaving ATR, HE1, and WG3 during the first 60 seconds of start-up

Conclusions

Fuel processing of infrastructure fuels on-board the fuel cell vehicle will have a higher probability of commercial success if fuel processors can meet the start-up target of 30 seconds. Argonne National Laboratory has designed a laboratory-scale fuel processor to start up in 60 seconds. The experimental apparatus will be used to study the feasibility of on-board fuel processing from the perspective of fast-start capability. Preliminary simulations suggest that the requisite hydrogen can be produced within 60 seconds. Experimental sequences will be used to confirm the simulations, to define practicable start-up solutions for meeting fast-start goals, and to identify the technical barriers that limit fast-start capability.

Acknowledgement

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